Natural Gas Engines – Reducing Greenhouse Gases

Howard Malm – Chief Technical Officer, REM Technology Inc.

Combustion Canada Conference September 22-24, 2003

Introduction

Reciprocating natural gas engines have a unique set of advantages and constraints with respect to greenhouse gas emissions. While methane, with a carbon to hydrogen ratio of 4 offers the highest energy per carbon atom of any hydrocarbon fuel, methane is in itself a greenhouse gas with many times the global warming potential of carbon dioxide. Minimizing the emissions of greenhouse gases from these engines has been achieved by improved engine control strategies and by the application of other improved practices. Other opportunities exist because of the wide availability of natural gas in urban environments through the implementation of local cogeneration where the waste heat from electric power generation can be used for building heating.

In the Western Canadian petroleum industry with an annual natural gas (NG) production of 170 Gm^3 (6 Tcf)[1], an estimated 1.4 GW (1.9 million HP) is used for field compression of natural gas to typical transportation pressures of 7500 kPa (1100 psig). Including gas processing and pipeline transportation brings this total to over 1.65 GW (2.2 million HP) of reciprocating engine power operating continuously. The estimated carbon dioxide emissions from these engines, assuming optimized operation, are 30,000 mega-tonnes (Mt) per year or 2% of the Canadian total. In practice, the greenhouse gas emissions from these engines are likely 20% to 30% more than need be due to poor operating practices, poor control and poor optimization.

In the first section of this paper, the improvement in engine efficiencies by better engine control strategies is discussed together with data showing the improvements achieved. In the next section, monitoring and operations changes to reduce the escape of methane are discussed. Finally, the potential for reduction of CO_2 by means of local cogeneration using NG reciprocating engines is reviewed and the options discussed.

Engine Control

The emissions from natural gas engines in the greenhouse category are carbon dioxide (CO_2), carbon monoxide (CO) and methane (CH_4). Other emissions such as non-methane hydrocarbons (NMHC) and nitrogen oxides (NO and NO_2) have a relatively short lifetime in the troposphere and do not contribute to the greenhouse gas (GHG) category. Carbon monoxide, for the purposes of this discussion is included as a greenhouse gas because the CO emitted to the atmosphere is gradually converted in a period of 1 to 4 months to CO_2. Methane is a GHG with significant global warming potential[2] (GWP) of 21 times that of CO_2 (100 year term) or 63 times (25 year term). Hence any escape of methane fuel to the atmosphere has a relatively large effect. While nitrous oxide (N_2O) is a significant GHG, it is produced in very small quantities in natural gas engines and can be ignored.

A natural gas engine can operate over a wide range of air-fuel ratios. The variation of emissions with air-fuel ratio is shown in Figure 1 for a typical NG engine used in gas compression. The emissions are plotted as a function of lambda, λ, the air-fuel ratio relative to the air-fuel ratio for stoichiometric combustion.

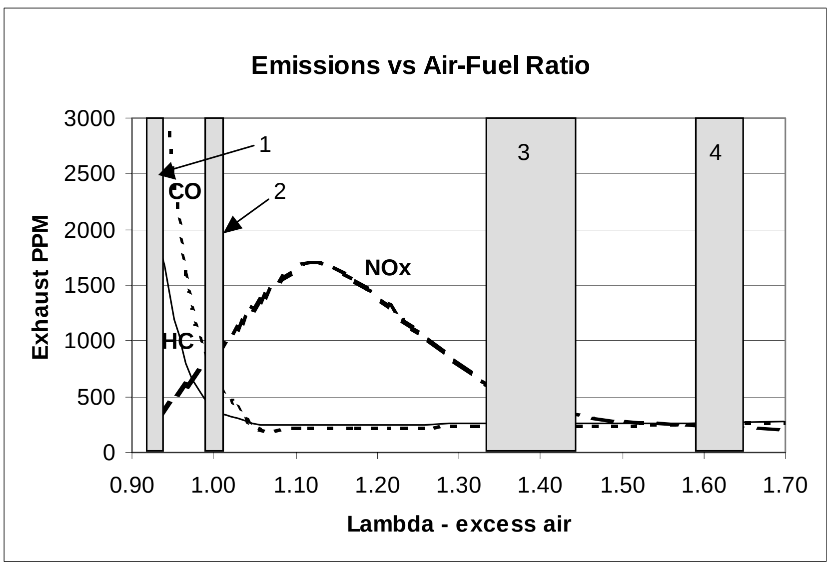

Figure 1 - Effect of air-fuel ratio

To reduce NOx emissions, many engines are operated on the rich side of stoichiometry ($\lambda < 1$) as shown by region 1. The unfortunate result is that both CO and hydrocarbon (HC) emissions, methane and non-methane, increase dramatically. Since the CO is oxidized to CO_2 the result is a much higher rate of GHG gas emissions from such engines. At stoichiometric operation, shown by region 2 the CO and HC emissions are still relatively high. While these can be reduced by a three-way catalytic converter, there is an energy cost, and a consequent CO_2 cost for stoichiometric operation. By moving the air-fuel ratio to the lean side, shown by regions 3 and 4, low NOx emissions can be achieved at the same time as low CO and HC emissions resulting in minimal CO_2 emissions per unit of mechanical energy. This is also observed as significantly improved fuel efficiency.

Recent innovations by REM Technology, which have improved the fuel-air management, air-fuel mixing and increased spark energy, have enabled operation with leaner mixtures (region 4) than previously possible, resulting in NOx levels below the 2.0 g/HP-h regulatory levels that exist in many locations.

More important, with respect to GHG, is the demonstrated fuel savings, and consequent GHG reductions in the conversion of rich burn engines to lean operation – changing the operating point from region 1 to regions 3 or 4. Audits on fuel costs before and after rich to lean conversion show a financial payback after 8 to 14 months of operation.

The fuel savings result from operating the engines more efficiently and with electronic controls so operation is not compromised by manual mis-adjustment. The efficiency of the engines is stated in terms of available heat from the fuel divided by the mechanical output power (brake power) and is known as brake specific fuel consumption (BSFC). The normal units of measure are J/W-h or BTU/HP-h. Figure 2 shows the results for the BSFC before and after the rich to lean conversion of 13 Waukesha engines, rated at 918 kW (1230 BHP). The average efficiency improvement was 12.5%.

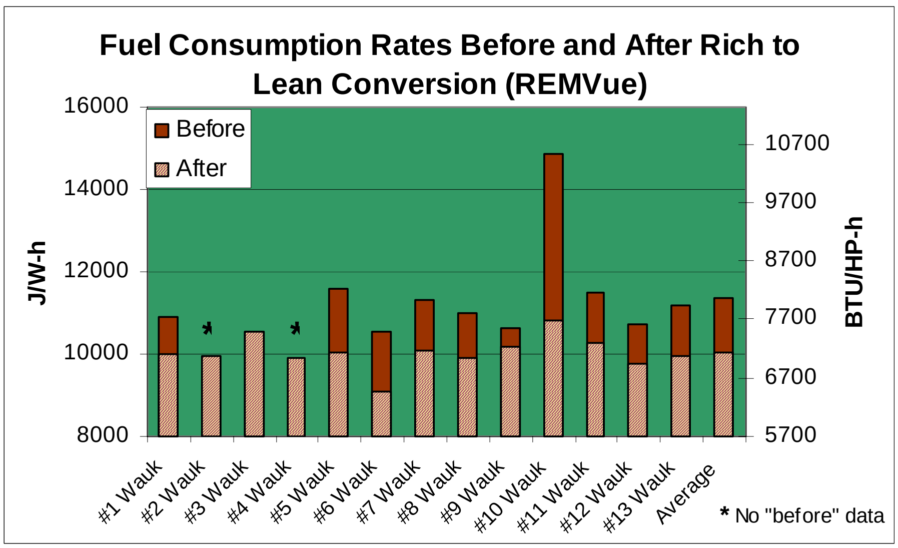

Figure 2 - Fuel efficiency improvement for rich to lean conversion

As a general rule most engines, when mechanically controlled and field-adjusted, tend to operate rich. Also, the relatively average age of the current engine fleet means that a large fraction of the engines do not have good controls. The results below for a wider range of engines show the benefits of electronic controls and leaner operation. The engine makes include many of the common engines in regular use – Waukesha (4 stroke), White-Superior (4 stroke), Cooper (2 stroke) and Clark (2 stroke). The reduction in fuel consumption rates and resulting GHG emissions range from 0 to over 38%. The average improvement was 22.8%.

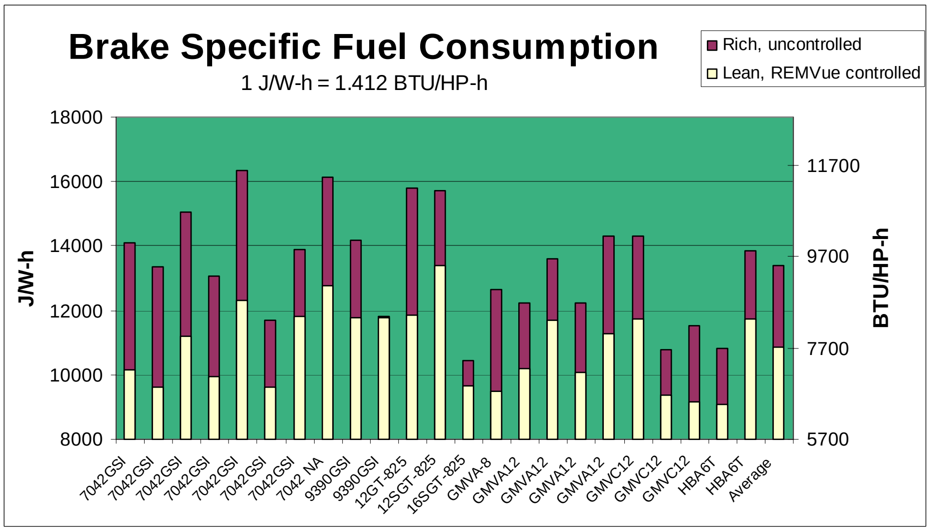

Figure 3 - Fuel Efficiency Improvement

A simple calculation shows the economics of improved fuel efficiency. For an improvement of 15%, a fuel heat content of 50 MJ/kg and a fuel price of Cdn \$5.00/GJ, the fuel saving for a 1 MW (1340 HP) engine operated 96% of the time is over \$75,000 per year. If a credit for CO_2 reduction of \$7.50/t is added, the total benefit is over \$81,000 per year, all while achieving a 15% GHG reduction from these engines. The economic payback of the improvement is often less than a year. In addition field data shows less cylinder head failure and less oil deterioration due to the lower exhaust temperatures leading to some reduction in maintenance costs.

Methane Emission Reduction

Mis-fire - A mis-fire is defined as the absence of an expected combustion event in an engine. In a multi-cylinder engine, failure of the methane mixture to burn has a serious effect. As mentioned previously, emissions of methane into the atmosphere have a much greater global warming potential (GWP) than carbon dioxide. While methane does eventually oxidize in an estimated ten years[3], the absorption spectrum of the methane molecule results in an effect that is some 65 times more than CO_2 over a 25 year period and 21 times more over a 100 year period. Assuming a mis-fire releases the total methane fuel charge in the cylinder to the atmosphere, the GWP from a methane-fueled engine with mis-fires can be estimated. The result is shown in figure 4.

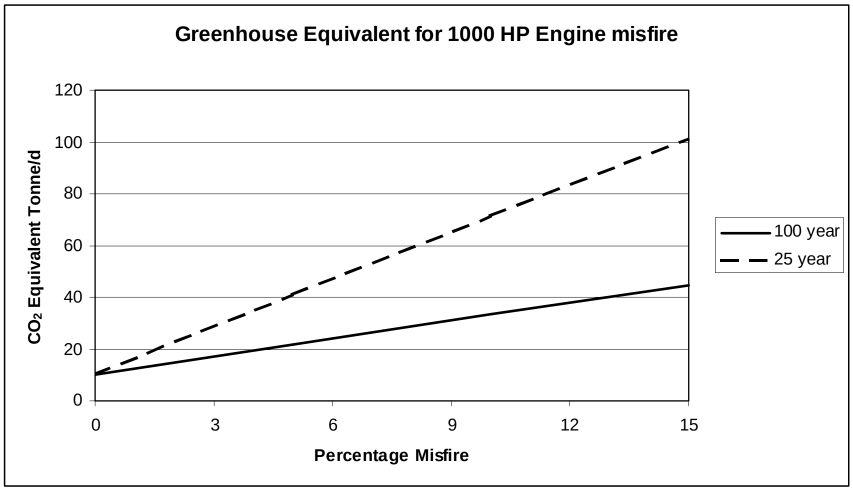

Figure 4 - Effect of a mis-fire on a NG engine

As an example, an 8-cylinder engine with 7 normal and one with a defective spark plug produces emissions with 4 times the GWP emissions of a well operating engine. Hence misfire detection and prompt correction are extremely important with NG engines.

There are several approaches to misfire detection. One is the on-line calculation of brake specific fuel consumption (BSFC) determined by measurement of load and fuel consumption. However a relatively large change (e.g. 5%) is required to initiate action. Another is on-line monitoring of individual cylinder exhaust temperatures with alarms placed on differences as shown here. This has proven to be effective in field practice. An example of a temperature difference display with alarm limits is shown in Figure 5.

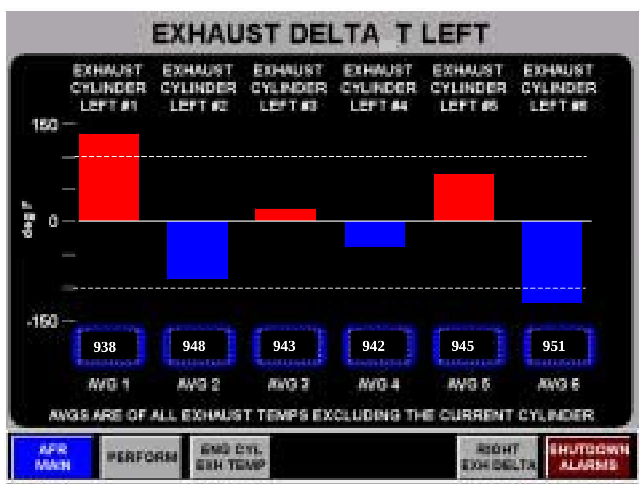

Figure 5 - Exhaust Delta T (REMVue)

More sophisticated methods such as exhaust pressure or exhaust oxygen monitoring at a sufficient rate to detect individual cylinder mis-fires hold promise but have not been tried in the field. Nevertheless, good fuel-air management from advanced control systems reduces the chance of mis-fire.

Engine Starting - An engine start with compressed gas uses 30 to 150 m^3 (standard cubic meters) or 1 to 5 Mscf. If the compressed gas is methane and there are 30 start attempts per year, an estimated 1.2 Mg/y of methane is vented to the atmosphere. Using a GWP factor of 25 brings this to a CO_2 equivalent of 30 tonnes per year.

Instrument Gas - Pressurized gas is used either for pneumatic controls or current to pressure (I/P) transducers for actuator power. In many installations pressurized methane (instrument gas) is used. Some of this gas is lost to the atmosphere. An I/P model in common use releases 30 scf/h or 5.4 Mg/y of methane to the atmosphere. Using a GWP factor of 25 brings this to a CO_2 equivalent of 130 tonnes per year. Obviously, if instrument gas is used, a regular leak survey is important to eliminate unintended methane releases.

The combined GWP equivalent of using compressed methane for starting and instrumentation is about 160 tonnes per year. While this is relatively minor compared to the CO_2 emissions from a 1000 kW engine, (4700 tonnes per year), methane emissions from these sources can be significant.

By replacing compressed methane for starting and instrumentation with compressed air, the GWP can be reduced at a relatively modest cost.

Blow-down - Another source of methane emissions is natural gas compressor and system blow-down. Opportunities exist here to minimize methane emissions by using transfer compressors or temporary storage of the blow-down gases.

Unburned Methane – All natural gas engines emit some unburned methane. The measured ranges are 3 to 5 g/kW-h for a small test engine[4] to and 6 to 7 g/kW-h for larger engines[5] which amounts to 1 to 1.5% of the CO_2 emissions. The methane comes mostly from the cold combustion chamber surfaces and crevices where combustion is quenched. Possible ways to reduce these emissions are improved designs to reduce crevices (for example above the top ring land) and the use of an oxidation catalyst for the exhaust gases.

Waste Methane - It is widely recognized that the decomposition of waste products (e.g. landfills, sewage treatment) generates methane gas. Using this gas for engine operation has the benefit of reducing methane emissions and producing electrical energy.

Cogeneration

In electrical generation using fuel combustion, the waste heat, some 60 to 70% of the total energy consumed, is transferred to the environment via air or water-cooling at the generation site. Since natural gas is widely available in many Canadian cities, there is an opportunity to use the waste heat for space heating with local generation of electricity by natural gas engines. The improved energy efficiency leads to a net reduction in GHG emissions.

To evaluate this for viability in the current economic climate estimates have been made for a moderate sized modern office building for which usage and costs are available. The building, located in Calgary, Alberta is hot water heated and contains just over 10,000 m^2 (110,000 sq ft) on three floors. The monthly electrical and heat consumption are shown for 2002 in Figure 6.

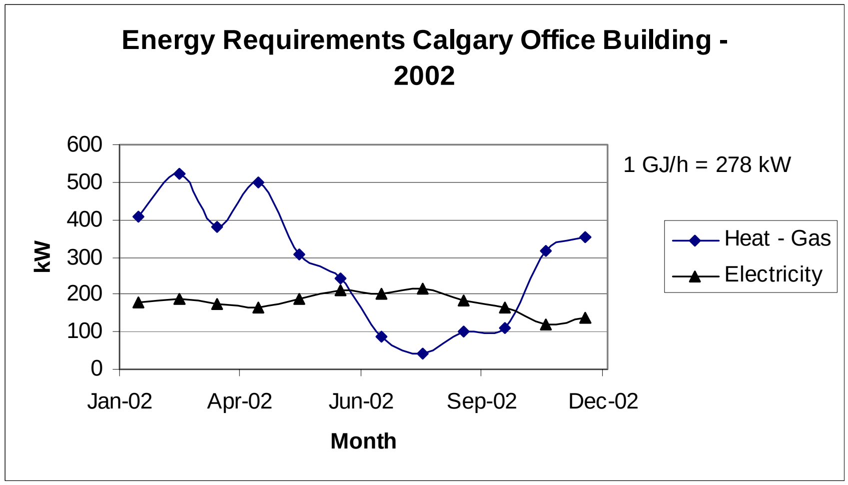

Figure 6 - Energy consumption for the example office building

During the year the delivered price for electricity varied between 8.7 and 11.4 cents per kW-h while the delivered price for gas varied between \$4.64 and \$7.88 per GJ. Figure 7 shows the monthly cost of the energy

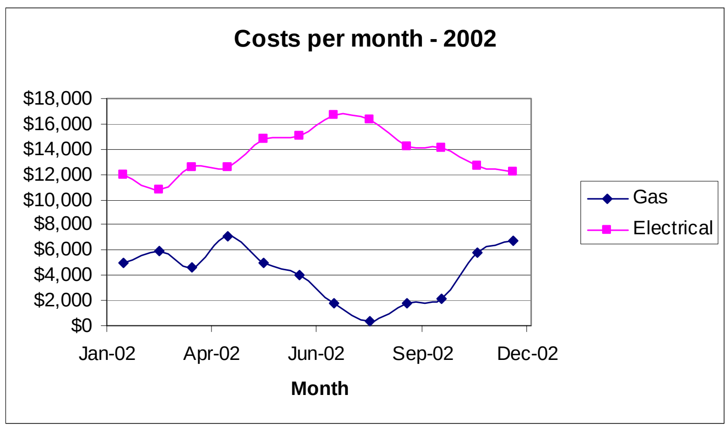

Figure 7 - Energy costs for the example office building

A typical natural gas engine uses about 30 to 35% of the fuel energy for mechanical power, which can be used for electrical generation. An estimated 50 to 55% of the fuel energy can be extracted at 80 to 90 deg C for space heating. The two main sources of the heat are the coolant and the exhaust gases.

Using the data for the example building, for a steady electrical load over a 24-hour period, local electrical generation can save approximately \$100,000 in purchased energy costs per year. To estimate the potential GHG savings, some estimates for sources of electricity are required. The GHG emissions from the Alberta grid is based on a efficiency for electrical production of 35% and a mix of 60% coal, 33% gas and 7% water/wind electrical production. For the example building, the estimated GHG production decreases from a total of 1800 tonnes/y at present to about 1100 tonnes per year with local cogeneration, a reduction of 700 tonnes/y or 39%.

For an electrical load, which varies by a factor of 2.5 over a 24-hour period and a 24-hour typical consumption profile, the benefits from local electrical generation are reduced by about 30%. To achieve this requires maintaining high engine efficiency over a wide load range. While this is difficult with constant speed generators, technologies that enable variable speed engine operation provide some promise. Work is underway by REM Technology on this subject.

Summary

Considerable opportunity for improvement exists to significantly reduce greenhouse gas emissions from natural gas engines. Since methane, the main component of natural gas, has considerable global warming potential, additional factors must be considered to minimize GHG emissions. One of the most successful initiatives to date has been achieved by improved engine control and the conversion of existing engines from rich-burn to lean-burn units. Estimated GHG reductions to date with a relatively small conversion fraction (about 2%) of the total fleet in Western Canada have amounted to over 35,000 tonnes per year. Other opportunities, which come from the desire to reduce methane emissions, are the prompt detection and correction or engine mis-fire and the reduction of the use of methane in place of compressed air. Lastly, there is opportunity to substantially reduce GHG emissions with local electricity generation where the waste heat can be used for space heating. While there are still regulatory and technical challenges, the potential for improvement is substantial.

References

[1] "Canadian Natural Gas and Climate Change" Canadian Gas Association March 2002
[2] "Introduction to Atmospheric Chemistry" D.L. Jacob 1999 Princeton University Press
[3] "Atmospheric Chemistry and Physics" J.H. Seinfield and S.N. Pandis 1998 John Wiley and Sons Inc.
[4] C. Reynolds, Dept of Mechanical Engineering, UBC - Private Communication
[5] "Waukesha Gas Engine Emissions Levels" Dresser-Waukesha Reference S8483-4